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Does non-linguistic segmentation still predict literacy in an L2 education? Statistical learning in Ivorian primary schools

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Abstract

Statistical learning (SL) is a learning mechanism that does not directly depend on knowledge of a language, but predicts language and literacy outcomes for children and adults. Research linking SL and literacy has not addressed children who first learn to read in their second language (L2), common in primary schools worldwide. Several studies have linked SL with childhood literacy in Australia, China, Europe, and the U.S., and we pre-registered an adaptation for Côte d'Ivoire, where students are educated in French and speak a local language at home. Recruiting 117 sixth-graders from primary schools in several villages, we tested for correlations >0.3 between SL and literacy with 80-90% power. We found no evidence for these correlations, but visual SL was correlated with L2 phonological awareness. Although this finding may suggest a role of SL in emergent L2 skills, it underscores the need to include L2 acquisition contexts in literacy research.

**Does non-linguistic segmentation still predict literacy in an L2 education?
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Learning to read: Global perspective

For millions of children, primary education--and specifically, learning to read--is undertaken in a second language. For example, over 14 million minority language speaking children in the United States are educated mainly or exclusively in the majority language (English), the topic of much second language acquisition (SLA) research (see August & Shanahan, 2006 for review). In many countries, primary schools use a national language natively spoken by a minority of the population to standardize education for children who speak regional languages. In Côte d'Ivoire, a West African nation of 26 million people (40% under age 15; CIA World Factbook, 2019), primary school students are educated in French while typically speaking a local language at home (Ayewa, 2018; Brou-Diallo, 2011). The same is true across many other sub-Saharan African nations where French or English serve as official or unofficial national languages for people speaking dozens of local and regional languages (e.g., Ethiopia: Mekonnen, 2009; Kenya: Jasińska, Wolff, Jukes, & Dubeck, 2019; South Africa: Schaefer & Kotze, 2019; Zimbabwe: Thondhlana, 2002) and in China where primary education is conducted in Mandarin regardless of regional dialect (Feng & Adamson, 2019). Worldwide, many millions of children's first steps towards literacy depend upon the--often simultaneous--acquisition of a second language.

A key concern in literacy research and intervention is identifying the antecedent skills of successful reading, also known as emergent literacy, wherein children acquire both oral language skills and decoding skills for a visual orthography (Storch & Whitehurst, 2002; Whitehurst & Lonigan, 1998). This developmental pathway from oral language to emergent literacy to literacy is more complicated in a second language (L2), where oral language competency, phonological processing ability, and print knowledge arise at different times and vary widely between populations (August & Shanahan, 2006; Chan & Sylva, 2015), and the relative importance of these oral and print skills in both first (L1) and second language (L2) for L2 literacy change with age (Jasińska et al., 2019). Particularly in low-income, agricultural communities like rural Côte d'Ivoire, many emergent readers are still acquiring basic oral and print L2 French in middle- and late-childhood, from a diverse set of L1s and L1 phonological abilities (Akpé et al., 2021; Ball et al., 2022; Jasińska et al., 2022). Therefore generalizations about the skills that underlie childhood literacy could be greatly improved by experimental paradigms that can be applied across children from many L1s and L2s, with varying exposure to print and varying ages of acquisition, i.e., non-

linguistic tasks which offer insights on individual differences in linguistic outcomes (such as literacy).

In this paper, we focus on statistical learning as a cognitive mechanism and, specifically, non-linguistic sequence segmentation as an experimental paradigm commonly associated with language learning outcomes (Saffran, 2003) in order to lay a foundation for understanding literacy in SLA contexts and in non-W.E.I.R.D. populations, that is, populations outside the western, educated, industrialized, rich, and democratic settings where psychology research is often performed (Henrich, Heine, & Norenzayan, 2010). Studies on literacy outcomes for children in the United States, Australia, Norway, and China have previously identified non-linguistic visual and auditory statistical learning as significant predictors of children's literacy skills (e.g., letter, word, and sentence reading) in different languages while not depending on any language-specific knowledge for the SL task itself (Arciuli & Simpson, 2012; Qi et al., 2019; Torkildsen et al., 2019; Tong et al., 2019), offering a possible common ground on which to study children learning to read in any language. However, very few studies have tested children in non-W.E.I.R.D. educational settings (although see Tong et al., 2019 for an exception), and none have tested children in their second language (but see the review of adult L2 studies below).

We proposed a pre-registered adaptation of non-linguistic statistical learning tasks that are both deployable in settings with limited technological resources and culturally relevant for children in rural Côte d'Ivoire to widen the breadth of SLA and statistical learning research and to help inform literacy interventions in this region (Akpé et al., 2021; Madaio et al., 2019a, 2019b; Seri et al., 2019; Tanoh et al., 2019). Understanding the mechanisms that underlie L2 acquisition and literacy could offer insights for improving educational outcomes for children worldwide.

Statistical learning, language development, and literacy

Statistical learning (SL) is a domain-general cognitive ability that appears to be available early in life (Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996) and plays a central role in the theories of language acquisition (Saffran, 2003; Sawi & Rueckl, 2019; Romberg & Saffran, 2010). In SL experiments, participants are repeatedly exposed to stimuli in non-uniform combinations, sequences, or frequencies, resulting in learning of underlying probabilistic or contingency relationships. Statistical learning of transitional probabilities (e.g., the likelihood of one syllable to follow another in a speech stream) has been demonstrated in infants, children, and younger and older adults (Palmer, Hutson, & Mattys, 2018; Saffran, Johnson, Aslin, & Newport, 1999).

Statistical learning abilities may support early stages of language acquisition by helping to identify linguistic units (e.g., words) in natural speech among other irregular or unreliable cues

(see Saffran, 2003). SL appears to support syllable segmentation and word segmentation as early as 12 and 16 months of age respectively (Nazzi et al., 2006), well before the onset of reading, but SL also shows sensitivity to domain-specific experiences (e.g., music training improves performance in auditory SL; Vasuki et al., 2017), raising the question of whether language experience also boosts auditory and visual SL performance where the tasks include verbal stimuli. As a result, it remains unclear whether greater capacity for SL improves reading or whether learning to read tunes learners to valuable information for SL (Hung, Frost, & Pugh, 2018). Therefore, it is important to examine the role of domain-general SL in reading using non-linguistic stimuli.

Children's ability to segment auditory sequences into subordinate units (sentences into words, words into phonemes) and their knowledge of print principles (e.g., names and sounds of letters) are critical predictors of literacy (Storch & Whitehurst, 2002; Windfuhr & Snowling, 2001). These skills--segmentation and association--are closely analogous to statistical learning paradigms, and previous SL studies have explained differences in reading performance with both non-linguistic statistical learning (as in visual SL studies, e.g., Arciuli & Simpson, 2012, and auditory SL studies, e.g., Qi et al., 2019) and linguistic sequencing tasks (e.g., word order; Bogaerts et al., 2016). This apparent domain generality of SL supports accounts of one or many kinds of SL influencing reading outcomes, rather than reading acquisition influencing these many different SL abilities.

Extension of these findings to second language literacy remains limited, but the availability of SL mechanisms throughout the lifespan and their importance in L1 learning suggest a contribution to L2 literacy as well. A few studies find that outcomes for adult second language learners are predictable based on their performance in visual SL tasks (Frost et al., 2013; Yu, 2016) and that compensatory brain activity during L2 reading is inversely related to VSL performance (Yu et al., 2018). Frost and colleagues' (2013) study of adult L2 Hebrew learners found that the relationship between VSL and Hebrew literacy was similar in adult L2 learners as previously described for L1 readers of Hebrew, and the pattern learning ability measured by this VSL task was not a strong correlate of other alternative explanations for such a correlation (i.e., general cognitive abilities).

Auditory SL specifically may predict L2 oral proficiency, and in turn support L2 literacy, as in Yu's (2016) longitudinal study, which found that ASL was not directly related to L2 literacy outcomes but predicted participant dropout from pre- to post-test in a sample of adult learners of Chinese, suggesting that they may have been struggling more than their peers who remained enrolled. Qi et al.'s (2019) study of L1 points to a similar role for oral language: Phonological

awareness mediates the relationship of non-linguistic auditory SL and literacy. For children in primary education, the oral proficiency barrier is all the more relevant if classroom instruction occurs in the children's L2. Yang et al.'s (2013) simulations predicted that early-onset bilinguals could draw on the same statistical learning mechanisms to achieve literacy in both languages, but little experimental work exists against which to validate this model. The next section explores these similarities and differences between child L1 learners, adult L2 learners, and the child L2 learners in our population of interest.

Generalizing to learners in rural Côte d'Ivoire

In the broader global context, the question remains open whether the mechanisms underlying more commonly studied forms of acquisition, namely L1 literacy in children and L2 literacy in adults, will translate directly to children learning to read for the first time in an L2 (Chan & Sylva, 2015). Particularly when contrasting W.E.I.R.D. and non-W.E.I.R.D. populations (Henrich, Heine, & Norenzayan, 2010), crucial contextual differences in children's linguistic and educational experiences may shape the relationships between statistical learning abilities, emergent literacy skills, and ultimate reading outcomes.

The SL-literacy link has most often been demonstrated with relatively opaque orthographies--English, Chinese, Hebrew--where sensitivity to latent probabilistic structures is extremely important for skilled reading. The utility of SL might diminish in more transparent orthographies, where grapheme to phoneme conversion rules are more reliable. On the other hand, comparisons between narrower differences in transparency have found sparse evidence for any difference in SL's importance. Frost et al.'s (2013) study with adult L2 learners of Hebrew found both unpointed word reading (relatively opaque) and pointed pseudoword reading (relatively transparent) were significantly correlated with VSL performance ($r=0.43$, $r=0.57$, respectively) when tested within the same sample of participants. Yang and colleagues' (2013) simulations of Chinese and English predicted that depth of orthography changed how normal and disordered reading manifested in learners, while holding the statistical learning mechanisms between languages constant, and Tong et al.'s (2019) mixed sample of typically developing children and children with dyslexia found that individual differences in VSL were correlated with Chinese word reading ($r=0.46$) and orthographic awareness ($r=0.50$). Chinese and English, although different in relative depth, are both generally classified as opaque orthographies.

French, the language of education in Côte d'Ivoire, is highly transparent in the print-to-speech direction (less so in speech-to-print) and thus may put less demand on statistical learning abilities for mapping grapheme to phoneme than more commonly studied languages. Studies of semi-transparent (Norwegian and German) and transparent (Spanish) orthographies have

provided mixed evidence for an SL-literacy link. Torkildsen, Arciuli, & Wie (2019) found that VSL correlated with word reading ($r=0.30$) after adjusting for age in a group of 65 Norwegian children ages 7 to 13, but Schmalz et al. (2019) found that in German, neither word reading, nor pseudoword reading, nor letter bigram sensitivity (a measure of orthographic knowledge) were predicted by performance on either of two SL measures: an artificial grammar learning task (another form of sequence learning in SL) and a serial response time task (a motor-sequence SL paradigm). In a study of Spanish-speaking eight year olds, Nigro et al. (2015) found no evidence that implicit learning predicted either pseudoword reading or writing (although their experiment was designed to detect correlations greater than 0.50). If SL-literacy effects are present but mitigated in more transparent orthographies, larger sample sizes than those used in previous studies of opaque orthographies will be necessary to detect them.

In another major difference from previous studies, children learning to read in Côte d'Ivoire often begin to read words later (in part due to the educational focus on French; Ayewa, 2018) than the nominal onset of primary education (around 6 y.o.; Department of Strategies, Planning, and Statistics, 2018), bringing a different set of developmental parameters to the task. Although SL is available early in life (8 month old infants; Saffran, Newport, & Aslin, 1996), children, adults, and older adults (60-81 y.o.; Palmer, Hutson, & Mattys, 2018) are all adept at sequence learning. Visual SL abilities even appear to increase with age (Arciuli & Simpson, 2012; Raviv & Arnon, 2017) from childhood to adulthood. Children learning to read later in life could rely more on a better-developed VSL ability than younger children.

Bilingualism may also prove an important, though multi-faceted, contributor. By definition, children learning to read in an L2 are either bilingual or at least simultaneously undergoing second language acquisition, and Côte d'Ivoire specifically is home to over sixty local languages. On one hand, recent evidence suggests that bilingual status improves statistical learning abilities (Onnis, Chun, Lou-Magnuson, 2018; Wang & Saffran, 2014). On the other hand, Onnis et al. (2018) found that balanced bilinguals showed the greatest advantage, with greater dominance in one language yielding less advantage. In terms of balance between languages, children in rural regions who have widely varying levels of L2 exposure outside primary school and no print experience in their L1 more closely resemble speakers of minority languages, using two languages in discrete contexts of home and education, than they resemble children growing up in balanced bilingual environments. The bilingual advantage for SL described by Onnis and colleagues might not apply unless parents are frequent French speakers or consumers of French media.

Finally, there are methodological considerations that will impact studies of statistical learning in any rural, agricultural, or low-income setting. We have attempted to pilot laptop-based

experiments in the La Mé region in recent years and found that the children are not experienced with personal computers, while cellphones are ubiquitous and touchscreen smartphones are familiar (although not every family has one). In other studies with children in low- or middle-income countries (LMIC), timed cognitive processing tasks have been successfully adapted for touchscreen. Pelz, Yung, and Kidd (2015) reproduced age effects on children's exploration behavior observed in the U.S. with Tismane children of rural Bolivia using a touchscreen task. More recently, the RACER suite of touchscreen-based cognitive tests was deployed in Lebanon and Niger in a large norming study by Ford et al. (2019). In another application of RACER among both local and refugee children in Jordan, Chen et al. (2019) found that despite low familiarity with personal computers, children were able to learn and complete the tablet-based tasks in only a few minutes. While only about 30% of the children in Chen's study had personal computers in their homes, nearly 80% had cell phones at home.

Other Methodological Considerations

Some further important questions about statistical learning paradigms in any context remain open. The reliability of implicit learning tasks for detecting individual differences in children has recently been called into question (West et al., 2018). Measures with low reliability tend to underestimate the between-group effect sizes typically reported in developmental research (Conway et al., 2019), yet even when group-level differences are evidenced, this does not also validate individual difference estimates on the same measure (Krishnan & Watkins, 2019; West et al., 2019). This debate, regarding the reliability of implicit learning tasks, has focused on the serial reaction time (SRT) task, which shares elements with online (RT-based) measures of statistical learning.

Like other tests of implicit learning, the 2-alternative forced choice paradigm (2-AFC) used in most SL-literacy studies has also shown very weak test-retest and internal reliability for children (Arnon, 2019), despite significant group-level effects when learning is compared with chance performance. Some recent studies of SL in children have reported good internal reliability for 2-AFC tests (>0.80 in Torkildsen et al., 2019, Qi et al., 2019; see Table 1 below), while others do not (Tong et al., 2019), and some preceding studies do not report this statistic (Arciuli & Simpson, 2012; Nigro et al., 2015). Internal reliability is also lower for non-linguistic ASL than for VSL (Qi et al., 2019, <0.80 ; Arnon, 2019, 0.2 and 0.43). Although previous studies report good test-retest reliability of 2-AFC measures in SL for adults (Siegelman & Frost, 2013; Siegelman et al., 2018; Isbelin et al., 2020), none of the studies with children evaluate test-retest reliability. In sum, too few studies vary across too many parameters (cover task, stimuli, age, and disability) to generalize about why some elicit reliable 2-AFC responses and others do not, but the need to evaluate this metric in future work is evident.

Table 1. Summary of samples and findings in a few prior studies and the pilot study.

Study	Sample Characteristics	Size	Age range (mean)	2-AFC Reliability	Correlation between SL and literacy
Arciuli & Simpson (2012; Experiment 1) <i>Cognitive Science</i>	Typically developing children in Sydney, Australia Native, monolingual English speakers	38	6-12y (9;5) Kindergarten to Grade 6	VSL: Not reported	0.33-0.36 (VSL 2-AFC)
Frost et al. (2013) <i>Psychological Science</i>	Adults studying Hebrew as a second language American English speakers	27	Not reported (26y)	VSL: Not reported	0.43-0.57 (VSL 2-AFC; for change in literacy across two semesters)
Nigro et al. (2015) <i>Journal of Psycholinguistic Research</i>	Typically developing children in Spain Native Spanish speakers	26	8-9y (n.r.) Grade 3	VSL: Not reported	0.44-0.57 (VSL with word writing)
Qi et al. (2019) <i>Scientific Studies of Reading</i>	Typically developing children in greater Boston area, USA Native English speakers	32	8-16y (12;2) Grade not reported	VSL: 0.84-0.88 ASL: 0.78-0.79	-0.51 (ASL Slope with nonword reading)
Schmalz et al. (2019) <i>Scientific Studies of Reading</i>	Adults in southern Germany Native German speakers	84	19-62y (27;8)	AGL: Not reported	<0.20 (AGL & SRTT with word, nonword, and bigrams)
Tong et al. (2019) <i>Research in Developmental Disabilities</i>	Typically developing (37) and dyslexic children (35) in Hong Kong Native Cantonese speakers	72	7-8y (7;7) Grade 3	VSL: 0.56	0.39-0.50
Torkildsen et al. (2019) <i>Learning and Individual Differences</i>	Typically developing children in eastern Norway Native Norwegian speakers (47 monolingual, 8 bilingual households)	65	7-13y (10;3) Grades 2-7	VSL: 0.81	0.30 (VSL 2-AFC)
Pilot data reported here	Typically developing children in greater Adzôpe, Côte d'Ivoire Native Attié speakers, L2 learners of French	VSL: 46 ASL: 47	8-13 y (mean: 11) CM-1 (Grade 5)	2AFC: ≤ 0.20 VSL slope: 0.53 ASL slope: 0.10	see Appendix S1

Besides apparent differences in reliability or internal consistency, ASL and VSL findings suggest a broader divergence between auditory and visual modalities in the SL-literacy research. Namely, the respective relationships of non-linguistic ASL and VSL with literacy differ between studies. Yu's (2016) longitudinal study suggested that ASL was a better predictor than VSL of oral proficiency in adults, which might mediate literacy achievement. Qi et al. (2019) also found that non-linguistic ASL predicted literacy outcomes in children, and that an ASL-literacy relationship was mediated by children's phonological abilities while VSL was a poor predictor. This finding elaborates beyond previous studies of L1 and L2 learners (Arciuli & Simpson, 2012; Frost et al., 2013; Tong et al., 2019; Torkildsen et al., 2019; Yu et al., 2018), where VSL effects are primarily reported as significant predictors of literacy. These divergent findings highlight the need to re-examine the association between SL and emergent literacy, where oral language skills are important mediators of outcomes.

The Present Study

Do the differences between previously studied readers and children learning to read French in rural Côte d'Ivoire change the relationship between statistical learning abilities and literacy outcomes? To the extent that SL shapes emergent literacy, and given the vast differences in spoken and print language experiences among bilinguals, it is reasonable to imagine the SL-literacy relationship will differ across language and education environments. Arciuli and Simpson's (2012) seminal study linking VSL with reading abilities has been cited over 200 times (according to Google Scholar) and inspired many of the studies reviewed above. However, many important questions about the SL-literacy link remain unresolved, and understanding literacy beyond the W.E.I.R.D. context means including a second language acquisition perspective from bilingual communities and second-language classrooms.

In the sections that follow, we describe an adaptation of designs used in previous studies to link non-linguistic VSL and ASL with literacy outcomes in early L2-French readers in Côte d'Ivoire. Most importantly, we aim to determine whether a careful adaptation of the previous statistical learning paradigms to a common-but-understudied developmental context still finds significant links between SL and literacy outcomes. Better insight is needed on what tools, tasks, and sample sizes are necessary to detect such an SL-literacy correlation, so that researchers can begin to study the interactions between basic learning mechanisms (like SL) and the important educational and linguistic factors that shape children's language and literacy development and have not been represented in W.E.I.R.D. or high-income country (HIC) samples.

Method

We built on the design of Qi et al's (2019; hereafter Qi2019) statistical learning experiment wherein children completed target detection tasks during a sequenced presentation of visual objects (cartoon aliens) and non-linguistic auditory stimuli (pure tones). We made important updates based on our pilot research, which used similar SL tasks. Our present adaptation consisted of four major changes relative to Qi2019, which are further detailed in Table 2. All documents, materials, scripts, and data are available at <https://osf.io/6f8aw/>.

Table 2. Changes to method, as compared with experiment described by Qi et al. (2019)

Method	Qi et al. (2019)	Pilot Study	Present Study
Participants	n=32 adults (age 18-34) n=32 children (age 8-16)	n=46-47 children (age 8-13)	n=106 children (age 8-16)
Interface	Computer monitor with spacebar on keyboard	Tablet computer with touchscreen	Tablet computer with touchscreen
Practice	Two practice trials with the target alien	Up to 64 trials with cartoon monsters in random sequence until criterion accuracy. Two prompts to touch the target response image during introduction to cartoon alien task	72 trials with cartoon monsters and sounds in random sequence Two prompts to touch the target response image during introduction to cartoon alien and environmental sound tasks
Visual SL Stimuli	Aliens from Arciuli & Simpson (2012)	New hi-color aliens from Schneider et al. (2020)	New hi-color aliens from Schneider et al. (2020)
Auditory SL Stimuli		Unchanged (Qi2019)	Environmental sounds (see Shufaniya & Arnon, 2018)
VSL task context	Aliens boarding a spaceship	Interesting animals boarding a bus	
ASL task context	Aliens playing musical instrument	Bus driver playing music on the radio	Bus driver playing sounds on the radio
Literacy measures	Woodcock Reading Mastery Test, W-J III Test of Achievement	French Early Grade Reading Assessment (EGRA)	
Phonological ability measures	Comprehensive Test of Phonological Processing	French phoneme identification, deletion, and segmentation	
Nonverbal intelligence	KBIT-2 with culturally specific object associations	TONI-4 with abstract polygon patterns and both French and non-verbal instructions	

First, the experiment was delivered on a tablet computer with touchscreen interface instead of a laptop computer. Second, prior to performing the primary SL tasks, children completed a practice target detection task with different audiovisual stimuli that occurred in an unstructured (random) order to familiarize them with the task demands and the touchscreen interface. Third, Qi2019's narrative of aliens boarding a spaceship and playing alien music was replaced with "interesting animals" (the same alien images) boarding a familiar bus and a radio playing music. Fourth, we substituted twelve distinct environmental sounds (previously used by Shufaniya & Arnon, 2018) for the pure tones used in Qi2019 and in our pilot.

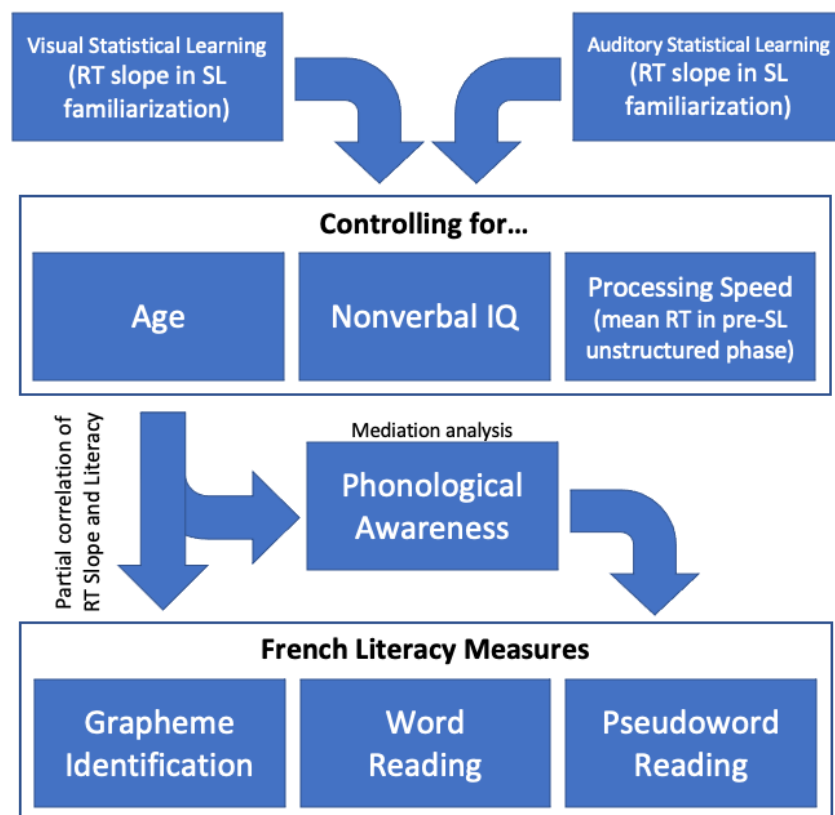


Figure 1. Measures in the present study include change in RT during a statistical learning task, three literacy measures, a phonological awareness task, and controls for age, nonverbal IQ, and average response speed in an unstructured target detection task.

Like Qi2019, our experiment owes its conceptual origins to Arciuli and Simpson's (2012; hereafter AS2012) study that first associated a non-linguistic VSL task with literacy in primary school children. In revisiting Qi2019's extension of AS2012 by testing the SL-literacy link with second language (L2) readers, we attempt to reproduce Qi2019's measure of response time slope

in the familiarization task, its correlation to reading measures, and test the mediation of the relationships between SL and literacy by phonological awareness in the SLA context. Figure 1 provides a graphical illustration of this plan, explained in detail in the sections that follow.

Participants

An ongoing literacy research program in Côte d'Ivoire examined French literacy skills in primary school children, already including hundreds of children from dozens of schools, with follow-up visits scheduled every six months from 2019 to 2022 (although covid-19 travel restrictions significantly reduced or eliminated most visits in 2020 and 2021). The students in this broader study were a randomly recruited pool of children in CM-1 (the equivalent of US 5th grade) classrooms across eight communities in the La Mé region of southeastern Côte d'Ivoire. Participants in this statistical learning study were in CM-2 and were recruited from schools in the control arm of the literacy study.

Participants in our present study ranged from 8-16 years of age. It is common for children in Côte d'Ivoire to enroll in school later than age 5 and to repeat grades, resulting in this highly variable age-range for a single classroom. On average, children in a previous sample of the 2019-2020 class started school at age 6.1 years, and 50% of the children had repeated at least one grade (some repeating multiple times), leading to the broad distribution of ages by the time they reached CM-1.

Further, although classroom instruction occurs in French, the children in our sample have varying exposure to French outside of school. Across the entire sample, 28% of children reported having a French speaking family member in their home. Most homes are primarily Attié-speaking (92%). Additional household languages in the intervention study sample include Baoulé (1%), Bété (<1%), and other regional languages (4% total).

Sample Size

We used the *pwr* library (Champely, 2018) in R (R Core Team, 2018) to estimate the minimum detectable correlations at power levels of 0.8 (typical in non-registered research) and 0.9 (standard for replication studies where failure to achieve statistical significance may be interpreted as evidence *against* an effect) for α of 0.05. Observed effects and sample sizes for studies in Table 1 are illustrated in Figure 2.

We estimated that a sample size of $n=95$ children would be necessary to detect a correlation of 0.3 between statistical learning score and literacy with 0.80 power for each correlation test, after correction for multiple comparisons ($\alpha=0.0167$) and with 0.90 power when uncorrected ($\alpha=0.05$). This approach balanced the rate of Type I error (0.05) against Type II error (0.20,

corrected; 0.10 uncorrected), while keeping the sample size reasonably achievable during a one to two week data collection effort. Our sampling plan was to recruit children until 106 children had completed the statistical learning, non-verbal intelligence, and French literacy tasks in their entirety (i.e., excluding early withdrawal), with the expectation of losing about 10% of the data for technical or experimental error, as reported in previous studies.

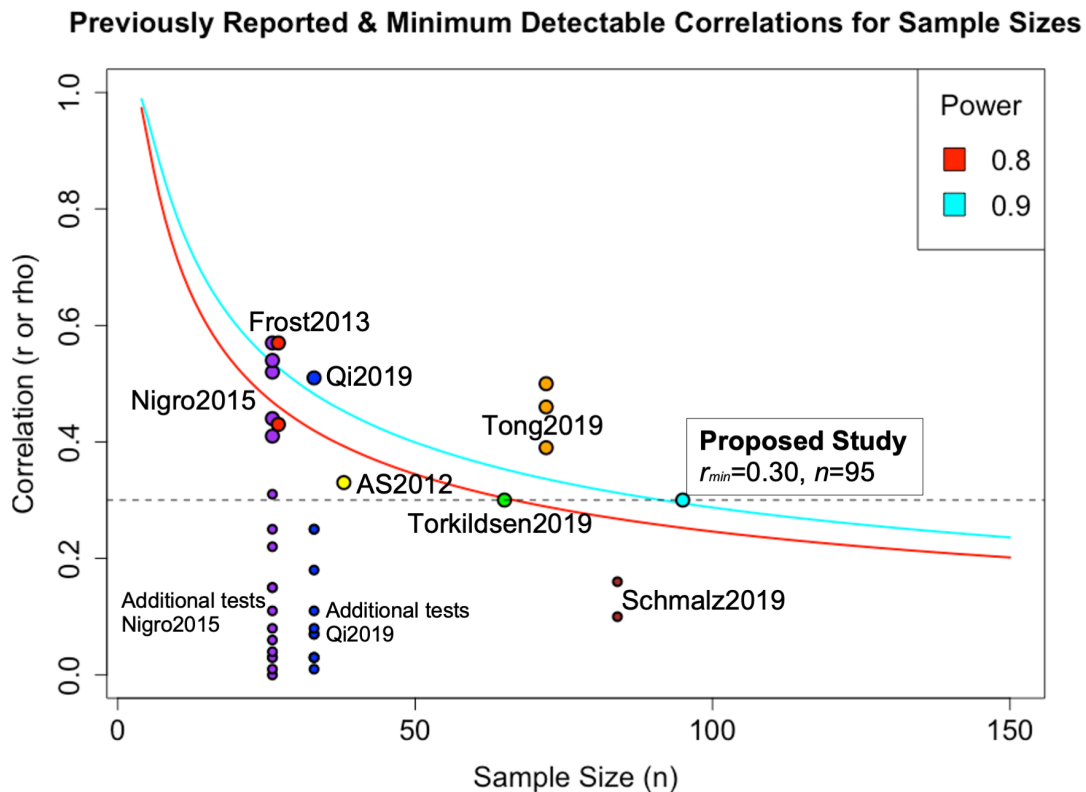


Figure 2. Reported effects for preceding studies of visual statistical learning and literacy, and power analysis for the present study. $\alpha=0.05$ (one-tailed), generated with the `pwr` package for R. Larger circles indicate reported statistical significance $p<0.05$. Studies correspond to results reported in Table 1.

Children were excluded if they were missing data for all of the literacy variables, did not complete the nonverbal IQ assessment, were unable to report their own age in years, or did not provide at least six correct hits in the target detection tasks, from which to estimate mean RT and RT slope. Children with incomplete literacy evaluations (e.g., completed grapheme reading but not the word and pseudoword exercises before withdrawing) were retained in the sample and analyzed on the tasks they did complete. Lastly, due to the distributed nature of the data collection (six to eight research assistants working at multiple schools), it was possible that final recruitment

would vary slightly from the target. We analyzed all children who met the criteria described above on the day that the total reached 106 (terminating data collection after that day).

Pilot Study

We piloted touchscreen adaptations of Qi et al.'s (2019) visual and auditory statistical learning tasks and French literacy, phonological awareness, and non-verbal IQ measures with children at two schools in a single community in early 2020. Both schools were part of the control arm of the wider literacy intervention in the La Mé region. Forty-seven children completed an auditory statistical learning task (ASL) using auditory pure tones, and 46 completed a visual statistical learning task (VSL) using cartoon aliens. The VSL data tasks were also reported by Zinszer et al. (2022), but that paper used linear mixed-effects models while this analysis closely follows the data processing and analysis steps described by Qi et al. (2019) for better comparison. Table 2 summarizes the experiment parameters. Complete pilot data and results are reported in Appendix S1, and our findings are summarized below. All data and scripts are available on our OSF repository: <https://osf.io/6f8aw/>.

Both SL tasks involved a cover task wherein children were asked to respond by touching the screen when they saw or heard a specific stimulus (target detection). Our pilot results showed a significant role of SL in the group-level RT slope for VSL, as children responding to targets in the predictable final position of the triplet sped up more than children responding to targets in the unpredictable initial position. However, 2-AFC measures of SL showed weak learning effects (<0.60 accuracy) and extremely low internal reliability (≤ 0.25) in both modalities. Our results also supported an important role for non-SL influences on the relationship between RT slope and literacy: (1) Children's performance (hit rates) in the pilot's brief practice phase, which lacked a learnable statistical structure, was one of the stronger predictors of literacy in multiple regression models, and (2) We observed strong correlations of RT slope across all measures of literacy when the target occurred in the unpredictable initial position.

The results of this pilot study highlighted the overwhelming effects of task proficiency or baseline processing speed, and the unreliability (at least in the present population) of two-alternative forced choice judgements as a measure of individual differences in SL. Consequently, our updated approach combined the visual and auditory practice exposure and increased the duration of the unstructured training. We did so to better acclimate children to the target detection task and obtain more data to estimate each child's unique processing speed and task-learning curve for randomly sequenced stimuli (where no learnable statistical structure exists). Further, we have adapted the ASL task for easier discrimination between stimuli (environmental sounds

instead of pure tones) and longer SOAs between stimuli to allow for slower RTs (SOA 750 ms instead of 480 ms).

Materials

The materials in this study were adapted from the previous studies to suit our target population, enable deployment in rural agricultural communities, and to fit within the scope of the literacy intervention study taking place in the region. Most significantly, while many of the SL-literacy experiments (and specifically the studies on which we are modeling this experiment) were conducted in English, the language of education in Côte d'Ivoire is French. Consequently, the measures of literacy were French instruments rather than those used by AS2012 and Qi2019. Further, these literacy instruments, the phonological awareness measures, and the general sample characteristics were determined by the literacy intervention study under which this experiment was being conducted, rather than selected specifically to replicate any previous SL-literacy study.

The preceding experiments used different measures of reading proficiency. AS2012 used the reading subscale from the Wide Range Achievement Test, fourth edition (Wilkinson & Robertson, 2006), which begins with individual letter identification (the first 15 items) and becomes increasingly difficult with the addition of words (55 items), including uncommon words and words with irregular spellings. Qi2019 reported several different reading measures for their child sample: Word identification and Word attack (pseudoword reading) from the Woodcock Reading Mastery Test (Woodcock, 1998), phonological abilities using the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999), and sentence reading fluency from the Woodcock Johnson III Test of Achievement (Woodcock, McGrew, & Mather, 2001). The sentence reading fluency subtest measures the time required by a participant to read a specific set of sentences and answer simple yes/no comprehension questions about them, standardized over the reading time and response accuracy.

We included a range of tests of French knowledge to accommodate different reading abilities of our population. In the present study, we tested grapheme/letter reading, word reading, pseudoword reading, and phonological abilities to cover most of the literacy measures reported in AS2012 and Qi2019 (other than sentence reading, which most of the children cannot do).

Literacy assessments. Literacy tasks were obtained from the French version of the Early Grading Reading Assessment (EGRA; RTI International, 2009). Participants sound out 100 French graphemes and grapheme clusters (e.g., 'e', 'M', and 'ch'), read 50 familiar French words (e.g., 'lire', 'ami'), and read 50 French-like pseudowords (e.g., 'ja', 'bigé'). Each of the three tasks was timed for 60 seconds and delivered on paper, with items presented in a fixed order, and the child's

number of correct responses in that time window was recorded as their score. For children who did not provide correct answers on any of the first ten graphemes, the first five words, or the first five pseudowords, that instrument was stopped, and they receive a score of zero. See Appendix S2 for the complete inventories of graphemes, words, and pseudowords.

Our baseline measures conducted in October 2019 for that academic year's CM-1 students indicated that a quarter of the Treatment group participants could not read the first five words of our inventory, so grapheme identification provides a critical measure of individual differences. (Control participants were held out from this analysis, so they could participate in future SL experiments.) Instead of combining word and grapheme identification in a single composite measure (as in the WRAT-4), we used the French EGRA's separate measures of these two skills. These measures have yielded good internal reliability, as measured by the standardized Cronbach's α (estimated by itemScore in R package psych ver 1.9.12.31; Revelle, 2020) and split-halves reliability, outlined in Table 3.

Table 3. Descriptive statistics and reliability estimates for each new literacy instrument (measured in a parallel set of classrooms enrolled in Treatment condition, n=741-751).

Language Instrument	Mean [95% CI]	SD	Std. Alpha	Split-Halves	% 0 scores
French EGRA					
Graphemes	22.0 [20.6, 23.2]	18.5	0.93	0.93	4%
Word	9.8 [8.8, 10.7]	13.2	0.84	0.84	26%
Pseudoword	6.8 [6.0, 7.6]	10.7	0.87	0.88	42%
Phonological Awareness	15.2 [14.5, 15.9]	9.9	0.89	0.88	8%

Note: 0 scores indicates the proportion of children who scored a zero on the task. High rate of 0 scores suggests floor effects on the measure.

Phonological awareness assessment. Like Qi2019, we tested children's phonological awareness as a possible mediator between SL and literacy. It was possible that in the target age group, previous studies would have observed ceiling performance on this task, obviating its contribution to the analysis, but in previous years we have seen wide variation between children in phonological awareness. In these tasks, children completed 10 trials each of initial phoneme identification, initial phoneme deletion, final phoneme deletion (Bruce, 1964; Reutzel, 2014), and segmentation (Yopp, 1995) using common French words. A complete set of phonological awareness items are included in Appendix S2. Like the literacy measures, a large sample of data

from the Treatment group indicated that the phonological awareness task has high internal reliability (see Table 3).

Nonverbal IQ assessment. We administered the Test of Nonverbal Intelligence, version 4 (TONI-4; Pearson Assessments; Brown, Sherbenou, & Johnsen, 2010) to each child in this study to control for individual differences that were a significant covariate of SL in Qi2019. The TONI-4 uses patterns of polygons and textures and does not rely on specific cultural knowledge (e.g., being able to identify a sailboat). Further, the TONI-4 includes French language instructions and non-verbal instructions. Because this assessment is based entirely on sequence completion, it can be administered with minimal linguistic interaction if necessary and includes a training block participants must pass to demonstrate comprehension of the task before proceeding to the scored items. In pilot testing, children's mean raw scores were 13.3 ($sd=4.8$, $n=56$). In the absence of locally applicable norming data for the TONI-4, age-normed scores are not computed, and raw scores are compared for the purposes of estimating within-group individual differences only.

Tablet-based SL testing. Unlike most preceding studies in statistical learning, the present study was performed using a touchscreen interface on iPad tablets. The transition from personal computers and laptops (on which most previous SL experiments have been run) to tablets was informed by both the population we were studying and by the logistics of deploying the experiment. Almost none of our research sites had working electrical outlets in the classrooms, and most schools have only a few electrical outlets at all on the school grounds. Because iPads can be charged in advance and replenished from mobile, solar-charging battery packs, it is possible to deploy a few dozen tablets, whereas only a few laptops (at most) could be provided. Secondly, many villages cannot easily accommodate the large research team, and therefore all equipment has to be transported by van from a nearby city each day, between fifteen to ninety minutes away. Tablets are therefore essential for mobility.

Families in the treatment arm of the literacy intervention were polled about their usage of basic feature phones (with a physical keypad and limited software) and smartphones (touchscreen with more personal computer-like features). 92% of households reported having basic feature mobile phones, and 63% of households reported owning one or more smartphones, illustrating the relatively broad penetration of this technology even in rural communities. Based on the stratified sampling of classrooms within each village, we inferred that children in the control arm (drawn from the same communities and recruited for the statistical learning study) had similar exposure to mobile devices. Previous studies have found that tablets work well for developmental research in LMIC settings (Chen et al., 2019; Ford et al., 2019; Pelz et al., 2015).

Tablet training task. In a pre-SL training phase, children performed a target detection task on a sequence of 72 audiovisual stimuli, composed of six cartoon monsters (see Zinszer et al., 2022 for images) paired with six environmental sounds. Trials were 800ms in duration (sound during the first 500 ms) with 200 ms interstimulus interval and randomly ordered according to a uniform distribution of transitional probabilities. Each monster+sound combination appeared 12 times, but no underlying structure could be used to predict their appearance trial-by-trial. The duration of the unstructured training was half as many target trials as the VSL familiarization, informed by our pilot experiments in Appendix S1. The pilot showed increases in response time, suggesting task disengagement, halfway through the initial (less predictable) VSL task, which most closely resembles the unstructured training. Further, the total number of exposures was limited to 72 due to having both audio and visual stimulus files for each exposure, which presents a bandwidth limitation due to the necessity of buffering stimuli over the cellular network. The same target stimulus was assigned for all children, which they touched on the screen when it appeared. In the first 24 trials, 800ms feedback follows each touch, a smile (correct) or frown (incorrect). In the remaining 48 trials no feedback was provided, and mean RT was computed. None of the stimuli used in training appeared again in the VSL or ASL tasks.

Visual statistical learning. The non-linguistic VSL task involved a target detection cover task during the familiarization stream for the statistical structure described below (an adaptation of Qi2019). In the familiarization phase of this task, participants were presented with a sequence of images, drawn from a set of twelve unique images for each phase. One of the twelve images was identified as the target image, and children were instructed to touch the target every time it appeared on the screen. After identification of the target image (which involves two practice touches), the target detection task commenced. Each image was presented for 800 ms with a 200 ms ISI, timing parameters previously proposed by Arciuli and Simpson (2011) and used in Qi2019.

The order of twelve alien images was dictated by an underlying statistical pattern: The aliens were grouped into four triplets which must always co-occur in a specific order, i.e., ABC, DEF, GHI, and JKL. The triplets could occur in any order, as long as no triplet repeated. Consequently, within triplets, the transition probability from the first to second image (A->B) and from the second to third image (B->C) was 100%, while the transition probability from the third alien to the fourth (first of the next triplet, C->D, G, or J) was 33%. Participants were assigned one of the four terminal images (C, F, I, or L) and were asked to touch that alien when it appeared. Thus, the appearance of the target alien was completely predictable based on the preceding two aliens, if participants had learned the transitional probability structure underlying the sequence.

Auditory statistical learning. The non-linguistic ASL task involved a target-detection cover task during the familiarization stream, as in Qi2019. In the familiarization phase of this task, participants heard 12 environmental sounds previously tested by Shufaniya and Arnon (2018) for non-linguistic ASL, but arranged according to the same structure as the VSL task: four sets of triplets from twelve unique sounds. Pilot testing established that the pure tones used by Qi2019 were difficult to discriminate and advanced too rapidly for the children to respond (see Appendix S1). The environmental sounds were 500 ms in duration with a 250 ms ISI. Like the VSL task, children went through two practice exposures to the target sound effect during the task instructions and practiced touching a radio image each time they hear the target sound (see Appendix S3). Total time duration of the task was held constant with VSL, as in Qi2019, resulting in 32 target trials across 384 total exposures.

Statistical learning assessments. Statistical learning was assessed by two methods: Changes in response time to the target detection task in the SL familiarization phase and accuracy of identifying triplets from the SL familiarization in a post-task 2-alternative forced choice test. Each participant's response times (RT) to the target stimulus were modeled using a simple linear regression across the trials of the familiarization phase. A negative slope of RT over target repetition number occurred if participants learned to anticipate the appearance of the target based on the two preceding stimuli, an indication that they were learning the contingencies that define the stimulus sequence.

In this adaptation, we narrowed the analysis time windows relative to those specified by AS2012 and Qi2019: We only accepted responses recorded during the presentation of the target image or sound. Thus, the valid response window for VSL was [0, 800] ms around the onset of the target image, and for ASL was [-250, 750] ms around the onset of the target sound because we saw the best performance using +/-1 ISI in the ASL pilot (likely due in part to the short stimulus duration). These time windows were selected to maximize reliability of the RT measures and the hit rates. The coefficient for slope of RT over the target repetition number was planned as the measure of SL, if internal reliability of at least 0.50 was reached. If RT slope reliability did not reach that level, we planned to substitute the difference between mean RT (which showed much higher reliability in the pilot) and the baseline RT from the unstructured training task.

In the post-familiarization test, participants were presented with a set of two-alternative forced-choice (2-AFC) decisions between the statistically defined triplets (ABC, DEF, GHI, JKL) and four foil triplets (AEI, DHL, GKC, JBF). Participants made 32 such comparisons, with each of the four triplets and each of the four foils paired twice, once with the correct answer on the left and once with the correct answer on the right.

Procedure

Recruitment for the SL study occurred in March 2022, when most of the children enrolled in the literacy study were in CM-2 classrooms (the equivalent of US 6th grade) for the academic year 2021-'22. Basic demographics (age, sex, use of French at home), literacy, nonverbal IQ, and statistical learning were assessed in a single visit. Literacy and SL task order varied depending on researcher availability.

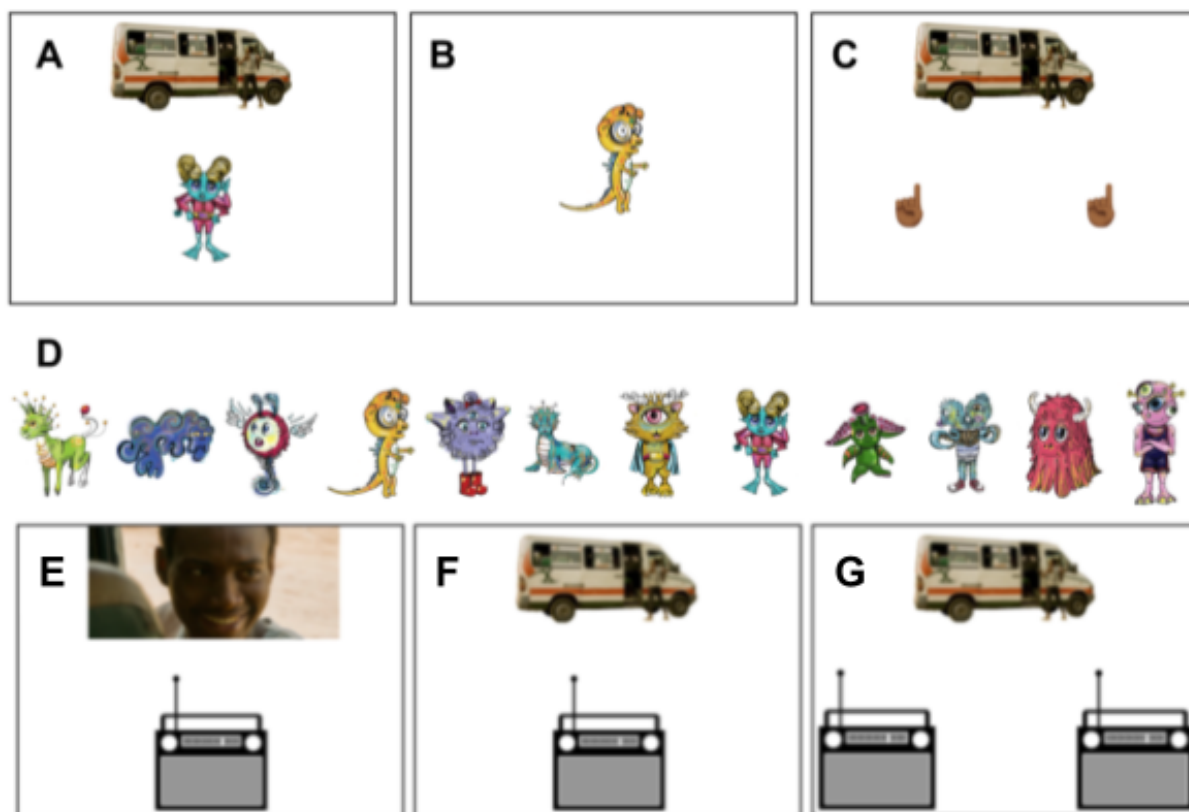


Figure 3. Presentation of stimuli in the familiarization and 2-AFC tasks. A. Identifying the target animal for the VSL familiarization task. B. Familiarization sequence showing alien on iPad screen. C. 2-AFC decision screen, where animal sequences have appeared in the positions denoted by the hand icons. D. Inventory of twelve aliens for the VSL familiarization task. E. Identifying the target sound for the ASL familiarization task. F. Familiarization sequence showing *gbaka* and radio on iPad screen. G. 2-AFC decision screen, where sound sequences have played simultaneously with the appearance of a radio on the left or right. Both radios appear at decision time.

Children completed the TONI-4 prior to participating in the statistical learning task. The TONI-4 follows a strict script provided by the publisher, in which the examiner asks the child to

complete a sequence or matrix of images with one additional image from a set of six choices printed on a single page. The researcher accompanied French language instructions with gestures prescribed in the nonverbal instruction set, in order to support the children's comprehension. Following the publisher's directions, a few practice trials were repeated until the child reliably produced the correct answers, and then the test commenced. Children normally start at varying test items (of ascending difficulty) based on their age, but we have found in piloting that the children do not conform to the test's age norms, and many need to move all the way back to the beginning of the test to establish a floor (five consecutive right answers). Therefore, all children were tested from the first item until they reach their ceiling performance (three consecutive wrong answers).

We implemented the SL touchscreen tasks on Apple iPads using Paradigm (Perception Research Systems, 2007). Instead of button presses, participants were instructed to touch the target stimuli when they appeared on the screen. The VSL and ASL tasks were contextualized similarly to the Qi2019 task, using a narrative about animals instead of aliens in the VSL task, a common form of transportation (the *gbaka*) instead of a spaceship, and the *gbaka* driver playing music on the radio instead of an alien playing guitar. We made these adaptations because children in the villages are not typically familiar with science-fiction media about aliens and spaceships. Figure 3 depicts key events in the VSL and ASL experiments, as they appeared on the iPad screen. Complete scripts with all relevant screen images, narrated text in French and English, and timing parameters are attached as Appendix S3, and the executable Paradigm scripts are available on the OSF.

Planned Analyses

Familiarization response times. As in the pilot data, we reported internal reliability estimates for the RT measures using split halves reliabilities. In the unstructured training, we reported reliability of mean RT (the regressor used in later analyses), and in the familiarization phase, we reported the reliability of the RT slope, being the SL measure of interest, and the mean RT.

We estimated the Spearman ρ partial correlations between RT Slope in both SL tasks and the three literacy measures (grapheme, word, and pseudoword reading), controlling for age, nonverbal IQ, and processing speed (mean response time for hits across the unstructured training phase). Crucially, we did *not* control for grade (as reported in some previous studies) because all of our participants were in the same grade, despite widely varying ages. Partial correlations were calculated based on the residuals of a linear regression model predicting RT Slope (with the predictors age, nonverbal IQ, and processing speed), and Tobit regression models predicting

each literacy measure (with the same predictors; see Zhu & Gonzalez, 2017 regarding Tobit regression for floor effects).

We adjusted for multiple comparisons using Dunn-Bonferroni adjusted p -values ($p < 0.0167$ for each of the three tests; Bonferroni, 1936; Dunn, 1961). Further, we compare the magnitudes of ρ and their confidence intervals to previously published correlations. In addition to the frequentist estimates, we report Bayes Factors (BF) for each of the partial correlations to quantify the evidence for or against the null hypothesis (Lee & Wagenmakers, 2013; Ly, Verhagen, & Wagenmakers, 2015; Morey, Rouder, & Jamil, 2015). The BF estimation for correlations is implemented by the BayesFactor package in R (Morey, 2018; Jefferys, 1961). We define our null hypothesis as the range $\rho = [-0.20, 0.20]$ because most related studies report significant correlations with magnitude greater than 0.30 (and some non-significant correlations greater than 0.20). The prior distribution is a shifted, scaled beta distribution with the parameters (3,3) following the “medium” width convention for the BayesFactor package.

Mediation analysis. We also tested the mediation of phonological awareness on these measures, as reported in Qi2019, using the residuals of the Tobit model for each literacy variable (described previously) as the outcome variable of a new regression. The test of mediation compared the contributions of ASL and VSL (RT slope, residualized) and the contribution of phonological awareness (residualized) as predictors of the literacy variables. We made this comparison using the R package mediation (Tingley et al., 2014) to determine whether the phonological awareness measure is a better predictor of literacy than ASL and VSL and whether ASL and VSL better predict phonological awareness than they predict literacy. The mediation analysis was handled as a conceptually separate comparison, again Dunn-Bonferroni corrected across the three literacy measures ($p < 0.0167$).

2-AFC response data. Our pilot research suggested that the post-familiarization two-alternative forced choice data were not likely to be informative about individual differences, consistent with some previous studies where this measure had low reliability in children. We repeated the pilot analyses on the new larger dataset to help improve our understanding of how children in this population perform the 2-AFC task and whether it has any merit for capturing SL effects. Participants' 2-AFC responses were evaluated for all 32 items, as well as the first 16 items and the first 8 items, with each score being further tested for internal reliability (split-halves) and correlation with RT Slope. If internal reliability for a 2-AFC test reached 0.70 (as in Qi et al., 2019; Torkildsen et al., 2019), we planned to compare that measure to the literacy variables following the same partial correlation and mediation procedures described for the RT data. However, given

the poor reliability in the 2-AFC data, we finally performed no planned comparisons with the literacy measures.

Results

Sample demographics

Data were collected over two weeks in early March 2022 from 17 schools in five communities around the greater Adzopé region of southeastern Côte d'Ivoire. Sixteen of these schools were control schools in the original study, and one child was re-recruited from a neighboring school because they moved there from a control school after baseline (and was not participating in the intervention). All but seven of the children were in CM-1 (fifth grade) at the time of baseline data collection in Spring 2019. Return visits were postponed by the covid-19 pandemic until 2022, and the children were in CM-2 (sixth grade), indicating that they had repeated one or both of these grades in intervening years. The remaining seven children were also enrolled in the CM-2 classrooms, but had not been present at the baseline data collection visit. Finally, 117 children met original inclusion criteria: able to report their age (or obtained from the teacher $n=14$), between 8-16 years old, and having completed the TONI-4 and at least one of the literacy tests. These children were 13.5 years old on average ($sd=1.3$, range: 10-16), 59 boys and 58 girls.

Table 4. Descriptive statistics for language, literacy, and nonverbal IQ measures.

Instrument	n	Mean [95% CI]	SD	% 0 scores
French EGRA				
Graphemes	117	43.8 [39.9, 47.8]	21.9	1%
Word	116	16.7 [14.0, 19.4]	14.8	10%
Pseudoword	115	12.0 [9.7, 14.3]	12.6	21%
Phonological Awareness	117	24.2 [22.7, 25.7]	8.9	2%
Nonverbal IQ (raw score)	117	13.6 [12.7, 14.5]	4.8	1%

Note: %0 scores indicates the proportion of children who scored a zero on the task. High rate of 0 scores suggests floor effects on the measure.

Language, literacy, and non-verbal IQ scores

Scores on the three French literacy measures, phonological awareness measure, and non-verbal IQ assessment are reported in Table 4. Scores were markedly higher than the baseline scores

reported three years earlier in Table 3. Five children accurately read all 50 French words, and one child accurately read all 50 French pseudowords. Three children provided accurate responses to all 40 French phonological awareness questions (an untimed task).

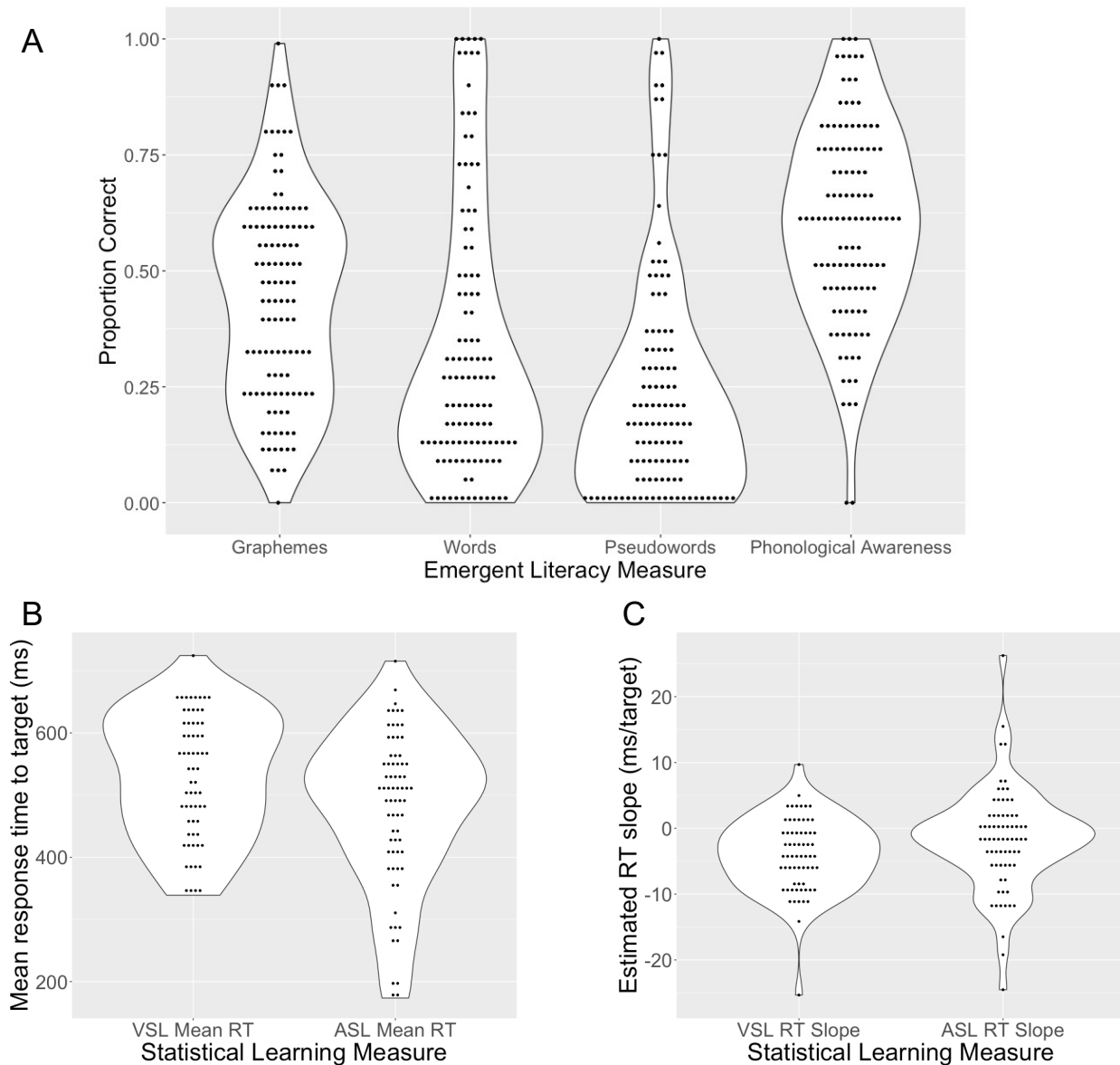


Figure 4. A. Density plots of scores on three literacy measures and phonological awareness. Scores are scaled as proportion correct out of total items. B. Mean response time for hits to target in ASL and VSL tasks. C. Estimated response time slopes (milliseconds per target image) for ASL and VSL tasks. Points on the plot are participant-level results.

Tablet training task

Among the 117 children included, 98 completed the tablet training task at the beginning of the statistical learning procedures. After the feedback phase of the unstructured tablet training task (24 trials, 4 target presentations), children saw and heard eight presentations of the audiovisual target without feedback and achieved a mean hit rate of 91% (95% confidence interval, hereafter CI: 0.88, 0.93; $sd=13\%$), with a minimum hit rate of 50%. False positive rates were extremely low, 2% (95% CI: 0.01, 0.02; $sd=4\%$), with a maximum false positive rate of 20%. The participant-level average response time for hits was 581 ms (95% CI: 568, 594; $sd=65$ ms, range: 438-743 ms), which had a split-halves reliability of 0.74 (estimated over 10,000 iterations, 95% CI: 0.742, 0.743).

Visual statistical learning

Of the 98 children who met inclusion criteria and completed the tablet training task, 89 completed the VSL task, with nine additional children's data lost due to interruptions of the cellular data connection. In the familiarization phase of the visual statistical learning (VSL) task, mean participant-level hit rate was 91% (95% CI: 0.89, 0.93; $sd=9\%$, range: 54-100%). No child was excluded for having an insufficient hit rate (meeting the criterion of 6 out of 24 target trials). The participant-level mean response time was 532 ms (95% CI: 512, 552; SD: 98 ms, range: 298-724 ms). False positive rates were extremely low (mean=0.003, 95% CI: 0.002, 0.004; $sd=0.01$, range: 0-3%).

Response time (RT) slopes for each child ranged from -25.3 to 9.7 ms/target, with an overall mean of -4.3 ms/target (95% CI: -5.4, -3.2; $sd=5.39$; range: -25.3-9.7; $t(88)=-7.9$, $p<0.001$). Internal reliability of the RT slopes was 0.68, assessed using split-halves estimation (10,000 iterations; 95% CI: 0.677, 0.680), which satisfied our pre-registered criterion of 0.50 or higher. We found no evidence that the RT slope was related to children's baseline response speed in the unstructured training task ($r=0.04$, $p=0.68$; 95% CI: -0.17, 0.25). Further, RT slope and RT intercept were, at most, weakly correlated ($r=-0.20$, $p=0.07$; 95% CI: -0.39, 0.01), suggesting that children who started out slowest (highest intercept) sped up slightly more over the course of the task (more negative RT slope) on average as compared to children who started out faster.

The mean response accuracy on the 2-AFC test was 0.519 ($sd=0.109$), which did not significantly differ from chance ($t(88)=1.67$, $p=0.10$). See Table 5 for details. However, the internal reliability of the 2-AFC scores was also low (Cronbach's $\alpha=0.34$; split-halves reliability with 100,000 cycles, 0.39). Analysis of the first eight and 16 items in the 2-AFC did not differ from chance either (mean accuracy for eight items: 0.480, 16 items; 0.513) nor did it demonstrate adequate internal reliability for further analysis (<0.30). Accuracy on the 32 item 2-AFC test was also uncorrelated with the RT slope measure ($r=0.01$, $p=0.94$; 95% CI: -0.20, 0.22).

Table 5. Descriptive statistics for statistical learning 2-AFC tests measured in pilot data.

Statistical learning	Mean [95% CI]	SD	Alpha	Split-Halves Reliability [95% CI]
Visual statistical learning				
All 32 2-AFC	0.519 [0.496, 0.542]	0.109	0.344	0.385 [0.384, 0.387]
First 16 2-AFC	0.513 [0.484, 0.542]	0.137		0.241 [0.240, 0.242]
First 8 2-AFC	0.480 [0.441, 0.520]	0.188		0.289 [0.288, 0.289]
Auditory statistical learning				
All 32 2-AFC	0.519 [0.502, 0.536]	0.079	-0.209	-0.211 [-0.213, -0.208]
First 16 2-AFC	0.514 [0.489, 0.540]	0.120		0.048 [0.046, 0.049]
First 8 2-AFC	0.532 [0.494, 0.570]	0.178		0.279 [0.278, 0.279]

Note: Bolded text indicates $p < 0.05$, uncorrected. 95% CI stands for 95% confidence interval of the mean.

Table 6. Partial correlations between SL measures and literacy measures

	VSL RT Slope				ASL RT Mean			
	n	ρ [95% CI]	p	BF	n	ρ [95% CI]	p	BF
Literacy Measure								
Graphemes	89	-0.11 [-0.32, 0.10]	0.285	0.12	71	-0.12 [-0.35, 0.12]	0.312	0.15
Words	88	-0.04 [-0.25, 0.17]	0.695	0.03	70	0.09 [-0.15, 0.32]	0.451	0.09
Pseudowords	87	-0.06 [-0.27, 0.15]	0.552	0.04	69	-0.01 [-0.24, 0.23]	0.952	0.04
Phonological Awareness	89	-0.29 [-0.47, -0.09]	0.005	11.96	71	-0.03 [-0.26, 0.20]	0.804	0.04

Note: Significance tests for literacy measures are compared to Dunn-Bonferroni adjusted $p < 0.0167$. Bolded text indicates $p < 0.05$ (corrected). 95% CI stands for 95% confidence interval of the Spearman correlation statistic.

Correlations with literacy. We estimated partial correlations between VSL RT Slope and each of the three French literacy measures (graphemes, words, pseudowords), controlling for age, non-verbal IQ, and mean response time in the tablet training task. Under the assumptions guiding our power analysis, we maintained at least 89% power to detect correlations between literacy and VSL greater than or equal to 0.30 ($n \geq 87$, $\alpha = 0.05$), with 76% power after correction for multiple

comparisons ($\alpha=0.0167$). None of the correlations were statistically significant (see Table 6). Bayes Factors provided moderate (<0.33) to strong (<0.10) evidence that the true correlations fell within the null hypothesis interval $[-0.20, 0.20]$ for all three measures.

Correlation with phonological awareness. The RT slope was significantly correlated with phonological awareness, with a Bayes Factor indicating strong evidence for a correlation outside the null hypothesis range ($\rho=-0.29$, $p=0.005$, $BF=11.96$, see Table 6). Further, phonological awareness was significantly correlated with all three literacy variables, controlling for age, nonverbal intelligence, and baseline RT (graphemes: $r=0.57$, $[0.41, 0.69]$, $p<0.001$; words: $r=0.66$, $[0.53, 0.77]$, $p<0.001$; pseudowords: $r=0.65$, $[0.51, 0.76]$, $p<0.001$) However given evidence against a relationship between VSL RT Slope and literacy, testing for mediation was not necessary. Nonetheless, we considered and rejected the possibility of complete mediation in further analyses in Appendix S4.

Auditory statistical learning

Of the included children, 87 completed the auditory statistical learning (ASL) task, with eleven children's data lost due to interruptions of the cellular data connection. Due to a software error, we had to reconstruct the target assignments for each child prior to computing performance statistics, based on their response biases. Of the 87 children, we successfully identified a target for 72 of them (and 15 showed no bias or preferred a sound in a different position). See Appendix S4 for more details and a validation of this approach using the VSL targets (which were recorded).

Mean participant-level hit rate was 58% (95% CI: 0.53, 0.62; $sd=19\%$, range: 15-91%) in the familiarization phase. One child was excluded for having an insufficient hit rate (below criterion of 6 target trials). After this exclusion, mean hit rate was 58% (95% CI: 0.54, 0.63), and mean response time was 479 ms (95% CI: 450, 508; $sd=125$ ms, range: 174-715 ms). The mean false positive rate was 5% (95% CI: 0.04, 0.05; $sd=4\%$, range: 0-14%).

Response time (RT) slopes for each child ranged from -24.5 to 26.3 ms/target, with an overall mean of -1.69 ms/target (95% CI: -3.50, 0.11; $sd=7.76$; range: -24.5-26.3; $t(70)=-1.84$, $p=0.070$), but internal reliability was 0.28 (10,000 split-haves iterations; 95% CI: 0.27, 0.29), which did not meet our pre-registered criterion of 0.50 for use. Instead, we used the mean RT during the ASL familiarization. The mean of participant-level means was 479 ms (95% CI: 450, 508; $sd=125$ ms, range: 174-715 ms), with an internal reliability of 0.84 (10,000 split-haves iterations; 95% CI: 0.84, 0.85). Response accuracy on the 2-AFC test was significantly greater than chance (mean: 0.519, $sd=0.079$, $t(86)=2.25$, $p=0.027$), but internal reliability of the 2-AFC scores was very low (Cronbach's $\alpha=-0.21$). See Table 5 for details. The first eight and 16 items in the 2-AFC did not exceed chance nor demonstrate internal reliability.

Correlations with literacy. Under the assumptions guiding our power analysis, we maintained 81% power to detect partial correlations (controlling for age, non-verbal IQ, and mean RT in the training task) between each of the three French literacy measures and ASL RT mean greater than or equal to 0.30 ($n \geq 69$, $\alpha = 0.05$), with 66% power after correction for multiple comparisons ($\alpha = 0.0167$). None of the correlations were statistically significant (all $p > 0.3$, see Table 6). Bayes Factors provided moderate (< 0.33) to strong (< 0.10) evidence that the true correlations fell within the null hypothesis interval $[-0.20, 0.20]$ for all three measures.

Correlation with phonological awareness. The mean RT was not significantly correlated with phonological awareness ($\rho = -0.03$, $p = 0.80$, $BF = 0.04$). Strong evidence ($BF < 0.10$) for the null hypothesis precluded any mediation of ASL effects by phonological awareness.

Discussion

We asked whether previously reported correlations between non-linguistic statistical learning (SL) and children's literacy existed for children in southeastern Côte d'Ivoire learning to read in their second language. Following extensive pilot research reported by Zinszer et al. (2022) and in the supplemental materials, we proposed a set of adaptations to existing visual and auditory SL tasks to measure individual differences among children who (1) have no experience using personal computers, (2) are unaccustomed to repetitive forced-choice test designs, and (3) are located in rural communities with limited access to typical laboratory infrastructure. Our results provided moderate to strong evidence *against* direct correlations (outside the interval $[-0.20, 0.20]$) between SL and L2 literacy, but we identified relationships between French phonological awareness and visual SL and between French phonological awareness and L2 literacy.

Do the adapted tasks effectively measure statistical learning?

High average hit rates ($> 90\%$), low average false alarm rates ($\leq 2\%$), and good internal reliability (> 0.68) in both the tablet training and the visual SL tasks indicated that our design accommodations were largely successful in engaging the children's attention and communicating task demands for the visual target detection cover task. Estimates of response time (RT) slope in VSL were overall negative on average, indicating that the children were gradually able to predict the appearance of the target from the underlying statistical structure. We also minimized the confound of overall task learning with our estimate of SL. Speed-up over time (RT slope) in VSL was, at most, weakly related to baseline response speed (estimated in the unstructured task) and the RT intercept (in the VSL task). These observations strongly suggest that the children's comfort with the target detection task was no longer confounding the RT slope and thus our estimates of VSL.

Results from the auditory SL task were less clear. Pilot testing suggested that this modality was generally more difficult, requiring a wider time window for children to respond and resulting in a large number of anticipatory and false alarm responses. The present experiment increased hit rates, decreased false alarm rates, and improved internal reliability relative to the pilot. These changes were small and might be attributable to either the tablet training task or to our use of Shufaniya and Arnon's (2018) environmental sound stimuli that were easier to discriminate and longer in duration than Qi et al.'s (2019) pure tone stimuli. Finally, although the estimate of the RT slope was negative on average, suggesting potential learning, it was not adequately reliable (0.28) to use as a measure of individual differences in SL. These task characteristics may yet be improved with refinement of the instructions for the target detection task.

In both modalities, the post-familiarization two-alternative forced-choice test remained an uninformative measure of statistical learning. This measure showed little or no learning in our sample, even on the group level, and it lacked internal reliability for assessing individual differences, even relative to Arnon's (2019) previous report on problematic 2-AFC testing in children. We also saw no evidence that shortening the test improved performance, and 2-AFC scores did not correlate with the RT-based measures of SL in either modality. Thus, even children who showed evidence of SL on the familiarization tasks showed no greater preference for statistically-defined triplets in the post-familiarization test than children who showed no SL in the familiarization.

Taken together, however, the combination of training task and VSL task made for an effective adaptation of a non-linguistic statistical learning paradigm, while the ASL task showed improvements relative to pilot testing and potential for further development. Based on the lower overall performance in the ASL task, the children may have relied on the visual cues more than the auditory cues during integrated audiovisual training. Modification of the training paradigm could attempt to contrast these auditory and visual cues in separate visual-target and auditory-target runs with randomly paired audiovisual stimuli, but would have to balance such rigor against time limitations.

Importantly, we found that these tasks could be implemented with light-weight touchscreen tablets that appealed to the children, could be transported easily, carried adequate charge for a half-day of testing, and could be recharged from portable battery packs and solar cells. These advantages would be compounded if future experiments excluded the time-consuming 2-AFC testing altogether, which took as long or longer than the familiarization task and—anecdotally speaking—appeared to bore and fatigue the children more than anything else in the testing battery.

Does the correlation between SL and literacy generalize to this population?

None of the three measures of French literacy (grapheme, word, or pseudoword reading) were significantly correlated with statistical learning in the visual or auditory tasks. Drawing on several previous studies of children and adults, we hypothesized that the correlation between SL and literacy measures would be at least 0.30. Our final samples were adequately powered (80% or higher prior to correction for multiple comparisons) to detect correlations of this magnitude, but the estimated correlations from this sample were very small, ranging in magnitude from 0.01 to 0.13. These values were well within a null hypothesis interval of [-0.20, 0.20], and Bayes Factors further indicated that the true correlations were very likely to be in this interval of no interest. In sum, we found no evidence that previously reported correlations between non-linguistic statistical learning and children's literacy generalized to our sample of emerging second-language readers.

Previous studies that have found correlations between SL and literacy differ in several ways from the present study. Previous studies with children have focused exclusively on native speakers of the languages being tested with average ages ranging from seven to ten years old (see Table 2 for details and citations). Children in Ivorian primary schools are considerably older on average. In our sample, ages ranged from 11 to 16 years old in the equivalent of 6th grade, with a mean of almost 14 years old. As L2 learners, the children also varied widely in their reading abilities, with about 11% unable to read a single word. Ullman's (2015) Declarative-Procedural Model proposes that older learners may draw on a different set of skills for L2 than their younger peers and first-language learners, at least in the initial stages of learning, tentatively offering a possible rationale for our findings. However, research with college-aged adult L2 learners (Frost et al., 2013) has also reported significant correlations between VSL and improvement in both nonword decoding and word reading over the course of an academic year. Thus, mere late exposure to a second language is not adequate to explain the present findings, but other differences between university and primary school students in L2 education could be explored.

Orthographic transparency is another important variable across studies, with relatively more opaque orthographies often featured in studies linking SL and literacy (Chinese: Tong et al., 2019; Hebrew: Frost et al., 2013; English: Arciuli & Simpson, 2012; Qi et al., 2019). Our findings fall more in line with studies of transparent orthographies like Spanish (Nigro et al., 2015) and German (Schmalz et al., 2019) that found scarce evidence of links between reading and SL. French is relatively transparent in the print-to-speech direction. We revisit the question of orthographic depth in the next section, where we consider whether a mediating role of phonological awareness in the SL-literacy relationship may reconcile these disparate findings between orthographies.

Lastly, the role of statistical power should be considered in understanding the inconsistency of results across the literature. Few of the studies linking SL and literacy have been adequately powered for detecting a correlation of the same magnitude as originally reported by Arciuli and Simpson (2012, $r=0.33-0.36$; see Figure 2), with the notable exception of Torkildsen et al. (2019). While some smaller studies (around 30 participants) have identified larger effects (correlations around 0.4-0.6), these studies have not consistently found relationships between the *same* pairs of variables (visual vs. auditory SL, reading vs. writing) and report a small number of statistically significant findings among several other correlations estimated below 0.3 (Frost et al., 2013; Nigro et al., 2015; Qi et al., 2019). Tong et al. (2019) found a significant relationship between SL and literacy after pooling dyslexic and normally developing readers into a single sample of 72 children, doubling the sample size but also increasing the variance along both measures over which to estimate the correlation (see Figure 2 of that paper). Among the largest sample sizes, Schmalz et al.'s (2019) study with 84 adults estimated correlations below 0.20 between related measures of implicit learning and reading. Collectively, these findings suggest that we still have very sparse data of the relationship between SL and literacy outcomes for children, that we should interpret the existing findings with caution, and that we must reconcile future studies' sample sizes with the hypothesized effect sizes.

How does phonological awareness relate to SL and L2 literacy?

We found strong evidence that better performance in visual SL (a more negative response time slope) was associated with higher L2 phonological awareness, with a Spearman's $\rho=-0.29$ ($p=0.005$, Bayes Factor=11.96, see Table 6). The same relationship was not evident with the auditory SL data. However, we found no evidence that phonological awareness mediated any relationship between VSL and L2 literacy. The mediating role of phonological awareness between non-linguistic auditory SL and L1 literacy was proposed by Qi and colleagues' (2019).

Besides our failure to find evidence for mediation, the correlation of VSL—but not ASL—to phonological awareness reverses Qi and colleagues' finding on SL modality. This reversal may be as simple as the VSL task providing a reliable measure of individual differences in SL ability in our task, while our ASL task was not adequately reliable. Differences between these two studies could also be attributed to the auditory stimuli, which were faster and more difficult to discriminate in Qi et al.'s study (pure tones) than the present study. Past research does support better ASL performance for faster sequences (Emberson, Conway, & Christiansen, 2011).

Phonological awareness's relationship with L2 reading aligns well with previous literacy studies in bilingual children where oral language skills provide a bridge between language competences. That is, phonological awareness in a first language predicts children's early reading

abilities in second languages (Chiappe & Siegel, 1999; Durgunoğlu, Nagy, & Hancin-Bhatt, 1993; Geva & Siegel, 2000). Artificial syllable segmentation tasks (which are structured similarly to the nonlinguistic SL tasks in the present study) are also correlated with adult participants' sensitivity to regularities in natural language word co-occurrence (Isbilen, McCauley, & Christiansen, 2022). In both phonological awareness and artificial speech segmentation, participants' ability to segment an unrelated signal (either the local language or an artificial syllable stream) predicts their sensitivity to the regularities of another, natural language. In the present study, we take one further step back, finding that a non-linguistic segmentation measure in a different modality (VSL) predicts the linguistic segmentation skills (phonological awareness).

The links between SL, phonological awareness, and literacy may also have implications for understanding orthographic transparency effects (see previous section). SL has generally been linked to reading in opaque (as opposed to transparent) orthographies, a distinction supported by Lee, Cui, and Tong's (2022) recent meta-analysis of differences between dyslexic and typically developing readers. Like the present study, previous studies failed to find links between SL and reading in more transparent orthographies (German: Schmalz et al., 2019; Spanish: Nigro et al., 2015), but these studies did not test phonological awareness. Phonological awareness may be most predictive in transparent orthographies. For example, Jasińska et al. (2019) found that phonological awareness was a stronger predictor of bilingual children's reading in a more transparent (Kiswahili) than opaque (English) second or third language. If a domain general statistical learning mechanism supports both phonological awareness and learning print-modality regularities, the direct relationship of domain general statistical learning to literacy will favor orthographic opaqueness (as seen in Chinese, unpointed Hebrew, and English), while mediated, indirect effects via phonological awareness appear weaker in pairwise correlation. Nonetheless, we found no such mediation effects in a relatively transparent orthography.

The causal direction of these relationships remains an open question, whether SL supports reading through detection of linguistic regularities, or whether skilled readers become more sensitive to distributional regularities in their input. The present study, while not offering a decisive causal test, provides some evidence for the former interpretation. Few, if any, of the children in our sample would qualify as advanced readers, meaning the cross-modal relationship between visual SL and phonological awareness has emerged in the absence of skilled reading.

Conclusion

We did not find support for our hypothesis that a direct correlation between non-linguistic statistical learning and literacy would generalize to children in rural Ivorian primary. These children differ from previously studied samples along multiple dimensions including age, reading

proficiency, educational experiences, and bilingualism. Despite these differences, we did discover strong evidence of a role for domain-general, non-linguistic statistical learning in phonological awareness, a crucial skill in emergent literacy. Previous studies have identified similar links between statistical learning and emergent literacy skills in children learning their first language and adults learning their second language, but this is the first study to investigate statistical learning in a common educational context: children first learning to read in a different language than they use in their homes and community. We have described a set of procedures enabling this research far from the laboratory in a rural, agrarian setting that is understudied in cognitive and psycholinguistic research. Insofar as these disciplines, especially studies of second language acquisition, aim to represent all children's development and language learning, future studies will continue stretching our experimental methods beyond the classrooms and laboratories of high-income, high-education communities.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Appendix S1. Pilot study.

Appendix S2. French literacy skills assessment.

Appendix S3. Statistical learning scripts.

Appendix S4. Further analyses for Stage 2 submission.